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UNIVERSITY OF DURHAM PHILOSOPHICAL SOCIETY.

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ON CERTAIN COLOUR PHENOMENA CAUSED BY INTERMITTENT STIMULATION WITH WHITE LIGHT.

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On Certain Colour Phenomena caused by Intermittent Stimulation with White Light.

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I would claim your indulgence for bringing a physiological subject before this section, on the ground that the results of physical experiments are sometimes misinterpreted from a want of knowledge of the factors that contribute to the physiological sensation of colour. As an example I may take the anomalous conclusions reached by Forbes and Young as to the velocity of light. To this point I shall refer again at the end of my paper.

It is most important to bear in mind that colour is not a physical term, it is a purely subjective term; it merely expresses the sensation produced by a certain kind of stimulus on a certain kind of cell. Undulations of a frequency about 400 billions per second produce the sensation of red colour in most individuals, while undulations of a frequency of about 700 billions per second produce the sensation of violet. Before light waves reach a colour-seeing organ, they cannot be said to have colour. No one would apply the term nauseous to waves of the sea, though under certain circumstances they may induce nausea in certain individuals. In books on physics the expression red waves is often conveniently used as an abbreviation for a set of waves of that period that induces a sensation of red in most individuals. From this use of the word a general idea has arisen that waves of this specific period are the only ones that can give rise to the sensation of red. It is my object in the present

paper to show that the colour sensation of red may be produced by other means.

In 1888, Mr. G: N. Stewart made some experiments on the law of Talbot with reference to the sense of application of light. The law of Talbot may require some little explanation. An electrical stimulus applied to a muscle-nerve preparation may be so weak and last such a short time, that no contraction of the muscle results; but if such stimuli are thrown in at a sufficiently short interval, a muscular contraction or rather a tetanus results. In other words stimuli which individually are unable to produce a muscular contraction may be summated, if they are thrown in at a sufficiently short interval. The same is true of the stimulation of the retina, at least in this sense that stimuli, which when isolated, act for too short a time to produce a sensation, may do so if allowed to follow each other rapidly, without diminishing the length of each. This can only happen, however, when each stimulus produces some impression, which though not amounting to a sensation, is a step on the way to one.

The law of Talbot may be stated thus:—Once complete fusion has been reached no alteration in the intensity of the resultant impression produced by a series of flashes takes place, however short the time may be during which each flash acts, provided that the number of flashes in a given time and the length of each stimulation be always kept inversely proportional. Complete fusion of stimuli here is analagous to tetanus of muscle. Is there any limit of time below which the individual stimuli cease to affect the retina at all, even when the frequency of repetition increases in proportion to the diminution of the time during which each stimulus acts? in other words is the retinal tetanus a complete tetanus, however short the duration of each stimulus? This is not the same thing as to ask whether there is a minimum time during which a stimulus must act in order to call forth a sensation. Such a minimum there certainly is. It lies lower the stronger the light; and above this

limit and below another, the physiological intensity of an impression arising from a stimulus of given physical intensity depends upon the time during which it acts.

Mr. Stewart's experiments were carried out with a rotating plane mirror. A parallel beam of light was allowed to fall on the rotating mirror in a darkened room, and in this way a series of very short flashes of light were received by the eye of the observer. Fusion of the flashes was obtained by increasing the speed of rotation of the mirror. He found that for the shortest stimuli he was able to use, there was no noticeable change of intensity of the sensation, once complete fusion had been reached, however rapidly the mirror was rotated. Even for the faintest light no definite variation appeared, that is, there was no noticeable departure from Talbot's law even when the duration of each stimulus was less than $\frac{1}{8,000,000}$ second. If there be a minimum length of stimulus below which no summation takes place, it certainly lies below $\frac{1}{8,000,000}$ second for the weakest light.

In the course of this investigation Mr. Stewart found that when the mirror was rotated slowly but with gradually increasing speed and a beam of light was reflected from it to the eye, a series of colour changes was seen. A description of a typical experiment will best explain what was observed.

Mirror driven by gas-engine, petroleum lamp the source of light.

S (1) = 7 turns a second of the rotating mirror.

S (2) = 10 ,, ,, ,, ,,

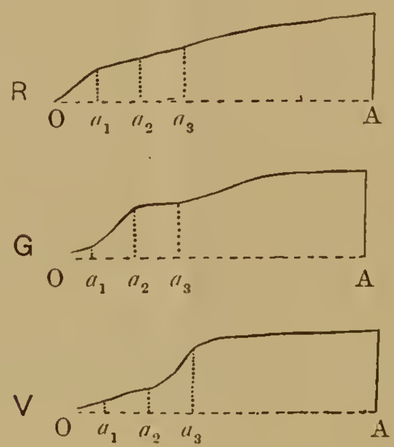
S (3) = 17 ,, ,, ,, ,,

S (1) A dark green band appears at each side of the broad greenish yellow band, which represents the successive images of the flame of the lamp. When the intensity of the illumination was increased, the broad band became violet, bounded by two green edges.

S (2) Dark green edges have disappeared.

S (3) Faint but broad yellowish brown band at edges, and yellowish brown mottling over the rest of image. When the intensity of the illumination was diminished, the whole image became reddish brown.

As the result of numerous experiments it was found that for any given intensity of light, there is a rate of revolution of the mirror with which violet preponderates, with a higher speed green preponderates, with a still higher speed red. A decrease of illumination puts the whole phenomenon further forward and corresponds to an increase of speed, while an increase of illumination puts the phenomenon back to an earlier stage and corresponds to a decrease of speed. Hence as the intensity of illumination at the edges is not the same as in the middle, the colouration of the edges is different from that of the middle.



Now all these changes take place about or below the speed necessary for complete and steady fusion of the separate flashes. The idea at once suggests itself that the phenomena are connected with the different course of the curves representing the excitation of the three groups of fibres of the Young-Helmoltz theory.

The adjoining figure (Fig. 1) represents the curves given by Mr. Stewart for the red, green and violet sensations. The time during which the stimulus acts is measured along the horizontal axis, and the intensity of excitation is denoted by the ordinate of the curve at that point.

Suppose that the stimulus considered be that of white light. If it be of the comparatively long duration indicated by OA, the excitation of each of the primary visual fibres—red, green and violet—will be equal, as is seen by the equal length of the ordinates. Consequently the resulting sensation will be white. But if the stimulus lasts for a shorter period as Oa3, the violet visual fibres will be more excited than the green and much more than the red fibres. Consequently the resulting sensation will be blue or bluish-violet. If the period of the stimulus be very short as Oa1, the red fibres will have the preponderating excitation, and a red sensation will result.

Fig. 2.

Fig. 3.

So far I have been practically only quoting from Mr. Stewart's paper. I must now attempt to give some reasonable explanation of the colours seen on this rotating disc.

Consider a disc half black and half white, the white part being marked throughout a quadrant by a curved black line. (Fig. 2). If the disc be now rotated counter clockwise at a speed of n revolutions per second, and the eye be fixed, a stimulus of white light will be received by the eye lasting $\frac{1}{4n}$ seconds. But owing to the persistence of the image the virtual duration of the stimulus will be $\frac{1}{4n} + a$ seconds, where a is a small fraction. When the speed of the mirror is such that $\frac{1}{4n} + a = Oa_1$ the line will appear red.

Now on reversing the rotation of the disc, the line appears blue. To explain this, we must draw attention to another physiological point.

When a uniform white surface is interrupted by a thin black line the black line is not so quickly taken up by the eye as a broad black surface. In this way the curved line will appear shortened to a greater extent than the after-image of the white extends over the black semicircle. Therefore in this case though the actual duration of the white stimulus is as before $\frac{1}{4n}$ seconds its virtual duration is $\frac{1}{4n}+\beta$ seconds where $\beta > a$.

On referring to the diagram we see that for a longer duration of the white stimulus Oa3, the violet ordinate is the greatest, and the green is next, so the colour between the two, or blue is seen. For a series of flashes following one another at an interval about that necessary for fusion, the ordinate corresponding to the length of each flash will still be the mean ordinate of the compound curve.

When the curved line occupies an intermediate position, the virtual shortening of the line will be less, as the white stimulus preceding it, will be less intense, for it has lasted during a shorter time. Consequently when a disc with four sets of lines as this (Fig. 3) is rotated four colours will be seen, red, stone yellow, dirty green and blue.

Colour Phenomena Observed by Forbes and Young.

The results of an elaborate series of experiments carried out by Forbes and Young on the velocity of light were published in the Philosophical Transactions of 1882. The method adopted was a modification of Fizeau's. It is unnecessary to describe the details. The source of light is placed behind a toothed wheel which can be rotated at a very rapid rate. The light passes out between two teeth, and is reflected from two distant mirrors placed nearly in the same line, but one

more remote than the other. When the toothed wheel is at rest the observer sees two stars side by side, of nearly equal brightness. When the wheel is in rapid rotation, the same thing happens for particular velocities. If after equality has been reached with one of these velocities, the speed be increased, the relative brightness of the stars changes. The star from the farther reflector gradually fades and finally disappears, the other reaching a maximum intensity to decrease in its turn. The star which has been first eclipsed will be the first to re-appear and will increase in brightness with the speed.

Now Forbes and Young observed that although white light was used, one of the stars was red and the other blue. Closer examination showed that when the brightness of either was increasing, its colour was red, and when its brightness was fading, its colour was blue. 'This they concluded to indicate a difference in speed of the waves of greater or less wave-frequency. Thus if the blue waves travel faster than the red, then the red waves will be eclipsed at a lower speed than the blue, so that as the speed of the wheel is increased the red waves will be first eclipsed and the fading image will appear blue. On the other hand, when the image is re-appearing after eclipse, the waves which travel slowest will be the first to gain admission through the adjacent tooth-space and the growing image will appear red. To test this point experiments were made with the red light and blue light of the spectrum formed by a prism, and from the average of the results the experimenters concluded that the blue waves travel about 1·8 per cent. faster than the red. This difference is so great, that in the absence of other support, the effects have not been generally accepted as due to a difference in velocity of the various waves, but it is surmised that the colouring is due to some extraneous cause not yet determined.'

The above is what Preston says in his theory of light.

Now will not Mr. Stewart's experiments explain this colour sensation? We have here an intermittent stimulation of the retina. The number of stimuli per second can be varied and so can the length of each; a small increase of the speed of the toothed wheel may extinguish one of the stars, *i.e.*, reduce its stimulation time to zero. A difference of speed of about 10 per cent. could produce an infinite difference in the brightness, and therefore in the time of stimulation. Accordingly the change in the velocity, so far as it affects the number of stimuli in a given time, may probably be neglected. We may consider in fact that the number of stimuli per second remains constant, while the length of each stimulation is continuously varied from zero to a certain finite maximum value, and from this value back again to zero. A glance at the diagram will show that as the stimulation time is increasing from O to Oa_1, the colour sensation produced will be red.

Further we know that the excitation takes some time to fade away, and that it fades away more slowly in the violet and green fibres than in the red. Helmoltz and Fechner have described a succession of colours in the after-image of a bright white object: 'the positive after-image goes quickly out of the original white through greenish blue into indigo blue, and then into violet.' Hence when the stimulation time is diminishing (or when the star is fading) the colour seen will be blue. For the excitation of the red fibres will rapidly fall away, while that of the green and violet fibres will for a time retain their pristine height. This is the explanation given by Mr. Stewart of the anomalous observations of Forbes and Young.

For monochromatic light Forbes and Young found that it required a greater velocity to produce equality with blue light than with red. Mr. Stewart suggests that this is due to the fact that 'the minimum difference which can be appreciated is not the same for each colour. . . Two similar white

lights which seem equal when looked at through a red glass may not appear equal when viewed through a blue glass.' This does not appeal to me. If one of the similar white lights is composed of the two complementary colours, yellow and blue, and the other is composed of all the colours of the spectrum, of course they will appear of different intensity when viewed through a blue glass.

I have found that when this disc is illuminated by sodium light on rotation the colours seen are almost the same as when it is illuminated by white light. The sodium light must therefore excite all three primary fibres, though of course to a different extent. But the colour phenomena due to a difference in length of stimulation time are still apparent. Hence to explain Forbes and Young's observations I would make the following suggestion. Suppose that when red light was used, the two stars appeared of equal brightness when the speed of rotation was from 410 to 418 revolutions per second, say 414. Now as the excitation of the violet fibres falls away more slowly than that of the red fibres, it is obvious that when blue light was used, the stars will appear of equal intensity during a greater range of speed. Suppose that they appeared equal when the speed ranged from 410 to 430 revolutions per second. The mean of this is 420. Forbes and Young would naturally conclude that a greater velocity was required to produce equality with blue light than with red light.

I would make a similar suggestion to explain this curious phenomenon of the disc, when it is rotated rapidly. Fixing the attention on the line which appears red on slow rotation, it becomes bluish or mauve on rapid rotation, and the line, is continuous or fusion is complete. Presumably in this case the intervals of non-stimulation are so short that the excitation of the violet and green fibres have not had time to fall away, while the red sensation has entirely faded. The blue sensation will increase to a certain maximum, on which will be superimposed numerous little flashes of

red sensation. Hence a mauve colour is seen. Fusion of the blue sensations will occur sooner than fusion of the red sensations, or if such an expression be allowed, blue tetanus will occur at a slower frequency of intermission than red tetanus. Hence a mauve colour-sensation is produced.